Forecasting Scour Related Mine Burial Using a Parameterized Model

Carl T. Friedrichs
School of Marine Science, Virginia Institute of Marine Science
The College of William and Mary, Gloucester Point, VA 23062-1346
phone: (804) 684-7303 fax: (804) 684-7198 email: cfried@vims.edu

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LONG-TERM GOALS

A major goal of the ONR Mine Burial Prediction (MBP) Program is to provide the operational Navy a prototype model for forecasting mine burial which works with a known and useful degree of accuracy in regions of strategic interest, defined initially as sandy inner shelves dominated by waves. In order to be useful under real world conditions, such a model must be reasonably accurate and reliable but also simple and fast enough to execute in a practical, straightforward manner by the Fleet. Thus it must parameterize the complicated and computationally intensive details of localized mine scour. In response to the above needs of the operational Navy, the long-term goal of this project is to demonstrate the practical utility of forecasting scour related mine burial using a simple parameterized model forced by readily available wave, wind and tidal forecasts.

OBJECTIVES

This project had the following specific objectives: 1. Post on the web continuous five-day forecasts of hydrodynamic variables for the MBP field sites during the MBP field experiment, including wave height, near-bed rms wave orbital velocity, wind speed and direction, wind-driven current speed and direction, tidal current and direction, and combined wave-current bed stress. 2. Predict scour-induced mine burial for the MBP field sites using a parameterized model and post continuously updated five-day forecasts of mine burial to the web. 3. Extend the parameterized model for scour burial to encompass additional new and existing field and laboratory data.

APPROACH

Our approach in forecasting wave conditions at the MBP field sites was to transform forecasts from the nearest grid cell locations provided by the NOAA Wavewatch III (WW3) global wave model. The WW3 model provides five-day forecasts of winds and waves with 0.25 degree resolution in latitude and longitude. We then used empirical transformations based on historical time-series of measured wave conditions at the MBP field sites to translate the model forecasts to local conditions. Predicted and observed wave heights compared very well during the MBP field experiments (Figure 1). Tidal currents were forecast based on harmonic analyses of existing current observations. Wind-driven currents were forecast from WW3 wind predictions by applying empirical correlations developed from correlations between WW3 hindcast winds and de-tided current observations.

Our approach in predicting mine burial was to apply well-established engineering relations for scour around seabed objects which indicate that the rate of scour around seabed objects occurs rapidly and

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then decreases in intensity as the depth of scour approaches an equilibrium depth for a given intensity and frequency of fluid forcing:

$$S = S_{eq}\,(1 - \exp(t/T_*)^P), \qquad (1)$$

(e.g., Whitehouse 1998; Sumer and Fredsoe 2002; Voropayev et al. 2003). In (1), S_{eq} is the equilibrium scour depth relative to the undisturbed far-field bed, T_* is the characteristic time-scale of the scour process, and P is a fitting coefficient of order 1 which depends mainly on the object's geometry.

Consistent with recent texts (Whitehouse 1998; Sumer and Fredsoe 2002), we treat the time-scale of scour as an empirical function, $f(\theta)$, of the skin-friction Shields parameter just outside the object's influence, normalized by dimensional parameters associated with the problem, namely object diameter (D), acceleration of gravity (g), specific gravity of sand (s), and median sand grain size (d):

$$T_* = f(\theta)\, D^2\, (g(s-1)d^3)^{-1/2} \qquad (2)$$

The Shield's parameter is given by $\theta = (\tau_b/\rho)[g(s-1)d]^{-1}$, where ρ is the density of water and τ_b is the magnitude of bed shear stress acting on sand grains away from the influence of the object. Consistent with recent texts, T_* is assumed to apply well to scour induced by currents, waves or combined flow.

To date, the only author to empirically derive coefficients for both (1) and (2) for the case of settling cylinders subject to scour is Whitehouse (1998). Whitehouse found $f(\theta) = 0.095\,\theta^{-2.02}$, P = 0.6, and

$$S_{eq} = 0 \text{ for } (\theta/\theta_{cr})^{1/2} < 0.75\,, \qquad (3a)$$
$$S_{eq} = 1.15\,D\,(2\,(\theta/\theta_{cr})^{1/2} - 1.5) \text{ for } 0.75 \le (\theta/\theta_{cr})^{1/2} < 1.25\,, \qquad (3b)$$
$$S_{eq} = 1.15\,D \text{ for } (\theta/\theta_{cr})^{1/2} \ge 1.25 \qquad (3c)$$

where θ_{cr} is the critical Shields parameter for the initiation of motion of non-cohesive sand.

WORK COMPLETED

We developed a website (www.vims.edu/~cfried/MBP) where we provided continual five-day forecasts of hydrodynamic conditions and mine burial for both the Florida and Massachusetts field sites during the MBP field experiments. Even though the main field experiments are now complete, we maintain our website as an archive of model input and output data and also provide access to web-based interactive mine burial models. Via the web, remote operators can use (1)-(3) to simulate mine burial at IRB and MVCO while adjusting their observation location, model parameters and hydrodynamic forcing conditions. During FY2004, the results of our collaborative work on mine burial prediction were presented at several venues (Friedrichs et al. 2004a,b; Trembanis et al. 2004a,b; Wolfson et al. 2004) and submitted for publication (Elmore et al. 2004; Richardson et al. 2004; Trembanis 2004).

RESULTS

Our main focus in FY2004 was a proof of concept that ocean wave forecasts could be used for real time web-based forecasting of mine burial. In the process of forecasting burial, however, we also needed to practically apply (1)-(3) in a predictive fashion. To use equations (1)-(3) in a real-time field situation, it was necessary to iteratively solve (1) to include time-dependent forcing. To do this, we translated scour depth to depth of burial by assuming the cylindrical mine immediately slid down into the deepest part of its own scour pit. The depth of burial relative to the seabed was then equal to the maximum depth of scour up to that point in time. It was simplest to further assume that the scour pit remained largely relict as the waves decayed.

Figure 1 compares our model predictions of mine burial by depth below the ambient seabed from our FY2004 work to MBP field observations collected off Florida and Massachusetts, assuming the scour pit remained relict as the waves decayed (Trembanis et al., 2004b). Observed burial by depth was calculated by low-passing pressure sensor data collected by the instrumented mines themselves (Richardson et al., 2004). Predicted burial by depth below the ambient seabed generally agreed well with the observed burial.

Predicting burial of mines by percent surface area was more complicated because there is no established theory relating the extent of burial of an object below the sand within a scour pit relative to the depth of the scour pit itself. One place to start was to try a simple proportionality such that the average elevation of the sand partially covering the mine within the scour pit was some fixed fraction of the depth of the deepest part of the scour pit. The rules of geometry could then be used to relate the sand elevation to surface area buried. For cases without extensive backfilling of the scour pit, our initial comparisons with field observations suggested that the average elevation of the sand within the scour pit relative to the deepest part of the pit was about 0.3 times the depth of the bottom of the pit.

Figure 2 compares our model predictions of mine burial by surface area from our FY03-04 work to MBP field observations collected off Florida and Massachusetts (Trembanis et al., 2004b). Observed burial by surface area was calculated from optical or acoustic sensors installed around the outside diameter of the mines. With no scour pit backfilling, the assumption that the average elevation of the sand above the bottom of the pit was 0.3 times the depth of the bottom of the pit worked reasonably well. However, observed burial by surface area appeared more variable than burial by depth. Although these two mine burial experiments did not exhibit significant scour pit backfilling, other mine burial experiments in 2001 and 2002 at the Massachusetts site did show extreme backfilling.

A simple alternative approach we used to include backfilling was to assume that the scour pit filled in continuously as waves decayed instead of remaining relict (Trembanis et al., 2004b). We used this alternate approach to reproduce percent burial by surface area observed off Massachusetts in winter 2001-2002 (Figure 3). Otherwise the modeling approach remained the same, with the same assumption that the average elevation of the sand above the bottom of the pit was 0.3 times the depth of the bottom of the pit. The mine continued to move downward with time when scour increased, but this time the mine got partly covered between events before subsequent scour re-exposed the partly buried mine.

IMPACT/APPLICATIONS

Our work with the Soulsby-Whitehouse equations has already impacted the strategy being taken by others to provide a working mine burial model for the operational Navy. Our MatLab formulation of the governing equations has been passed on to Paul Elmore at NRL, who is incorporating them in his prototype linked modeling system, and to Alan Brandt and Sarah Rennie at Johns Hopkins, who are incorporating the equations into their prototype expert system. Based on our early success with this simple parameterized approach at the MBP field sites, it is likely that the new model ultimately used for scour-induced burial by the operational Navy will build directly on our formulation.

(a) Indian Rocks Beach, Florida

(b) Martha's Vineyard, Massachusetts

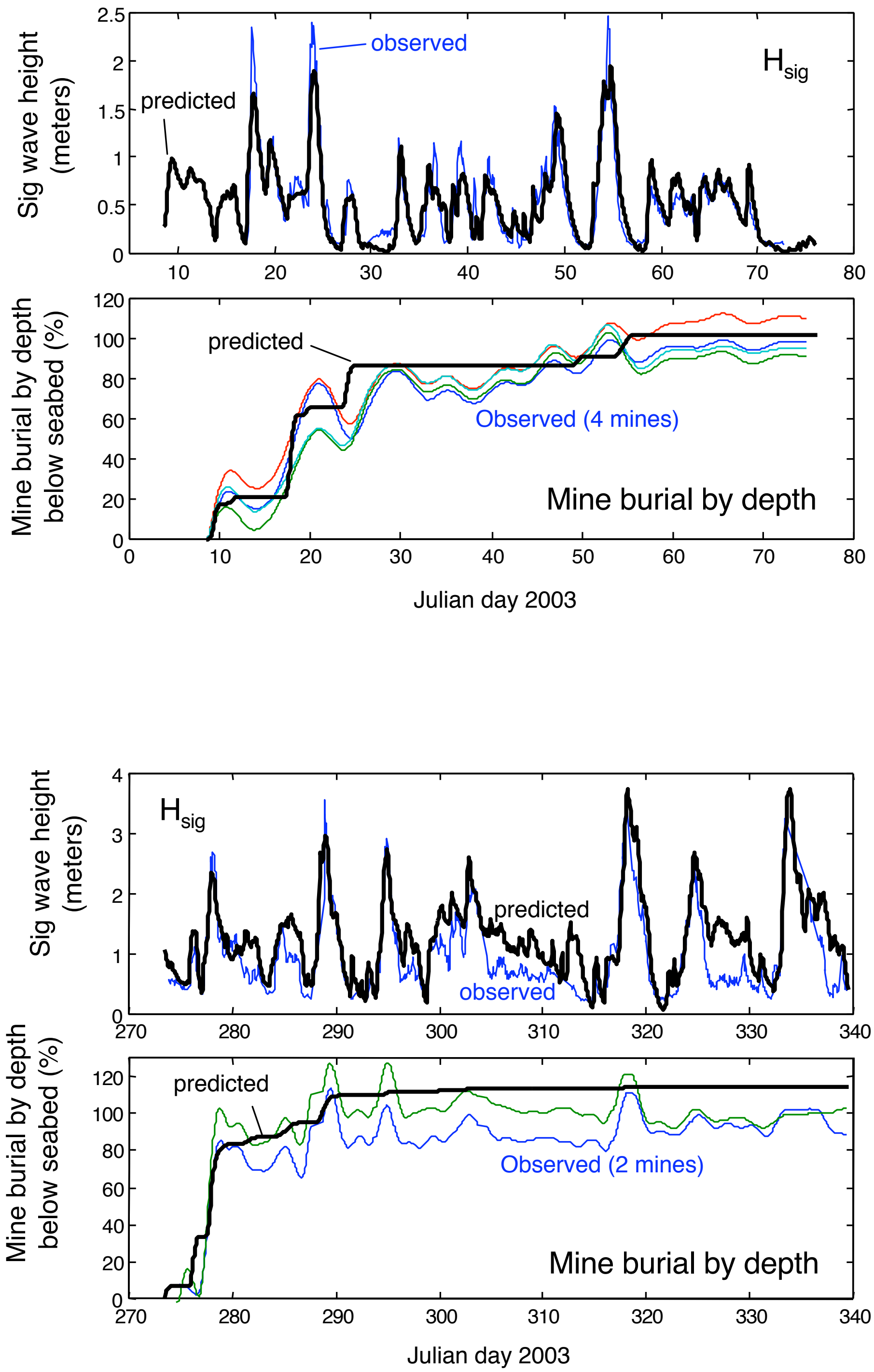

Figure 1. Comparison of model prediction to observations of significant wave height and percent mine burial by depth below the ambient fine sand seabed at the ONR MBP field sites off (a) Indian Rocks Beach, Florida, and (b) Martha's Vineyard, Massachusetts. The thick black lines are predicted values and the thin colored lines are observations. Observations of wave height and mine burial compare well with model predictions at both sites.

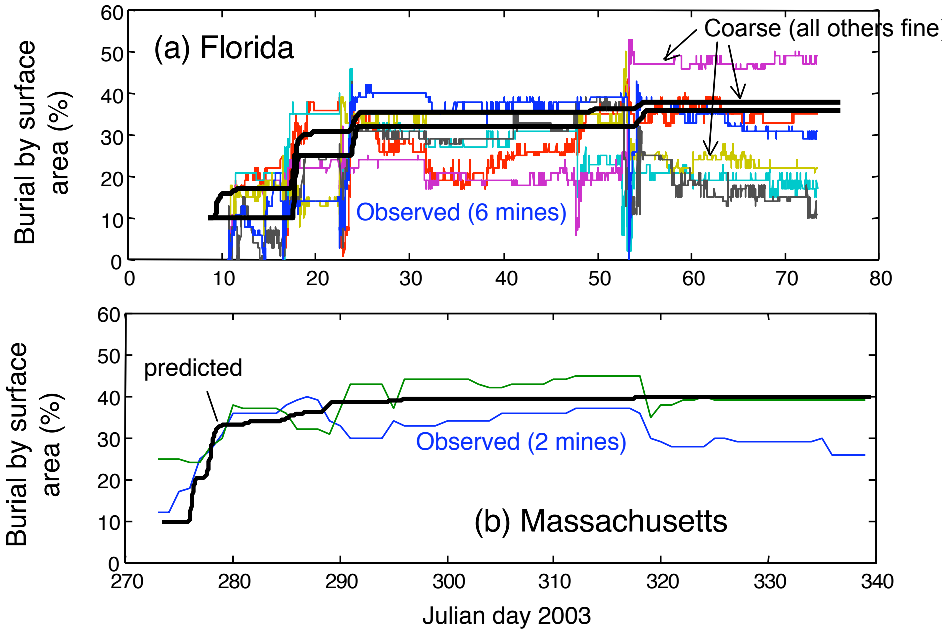

Figure 2. Comparison of model prediction to observations of percent mine burial by surface area covered with sediment at the ONR MBP field site off (a) Indian Rocks Beach, Florida (fine and coarse sand), and (b) Martha's Vineyard, Massachusetts (fine sand). The thick black lines are predicted values and the thin colored lines are observed. Observed and predicted mine burial by surface area compare well with model predictions at both sites.

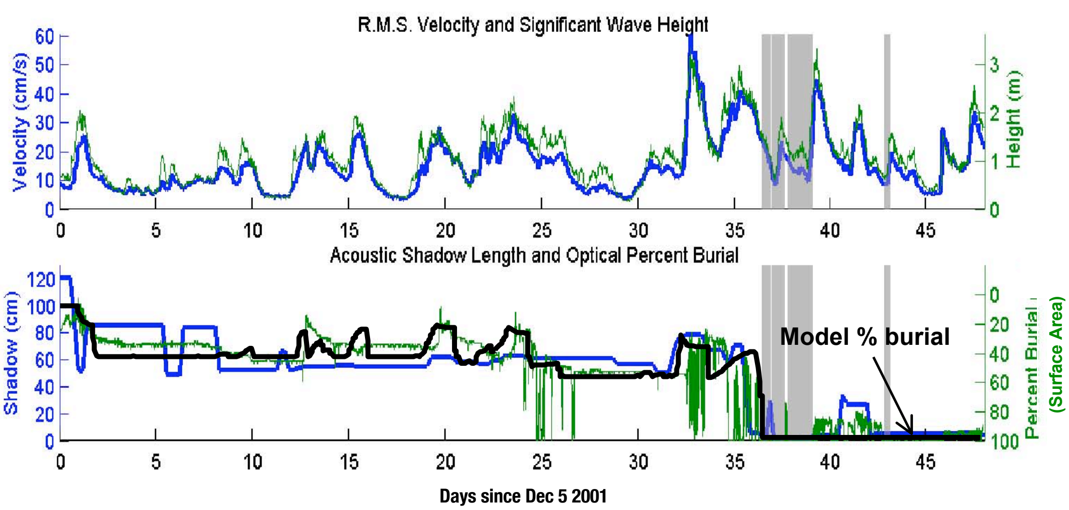

Figure 3. Data from the ONR MBP field site off Martha's Vineyard, Massachusetts. (a) Observed RMS bottom orbital velocity (thick blue line) and significant wave height (thin green line). (b) Acoustic shadow cast by mine (thick blue line) and percent burial by surface area covered with fine sand (observed is thin green line, modeled is thick black line), where modeled burial includes scour pit backfilling. The gray shaded regions indicate periods when fine sediment had filled the scour pit. Figure modified from Richardson and Traykovski (2002). Accounting for scour pit backfilling results in a good comparison between modeled and observed burial by percent surface area for this data set also.

TRANSITIONS

During a representative month of real time prediction coinciding with the MBP field experiments, our mine burial prediction website at VIMS was visited by nearly 3000 unique users from 43 countries. The top ten countries in order of decreasing number of hits were: United States, Canada, Japan, United Kingdom, Australia, Taiwan, Sweden, Finland, Netherlands, and Hong Kong. In addition, we have been corresponding one-on-one with Phil Mulhearn at the Australian Defence Science and Technology Organisation. As part of his own research into scour-induced mine burial, Dr. Mulhearn has begun comparing the output of our model to Marcelo Garcia's recent laboratory experiments on scour-induced burial of cylinders by waves.

RELATED PROJECTS

The following recent projects involving Friedrichs also focus on coastal sediment transport:

1. Upscaling Simple Models for Energetic Shelf Sediment Transport. Office of Naval Research (www.vims.edu/physical/projects/CHSD/projects/Euro).

2. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (www.vims.edu/physical/projects/CHSD/projects/CAREER).

3. The Role of Spatially Complex Shoreface Roughness in Sediment Transport and Deposition: A New Zealand Case Study and Model Development. National Science Foundation. (www.vims.edu/physical/projects/CHSD/projects/NewZealand).

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HONORS/AWARDS/PRIZES

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Friedrichs, C.T., 2000. Presidential Early Career Award for Scientists and Engineers (PECASE). Awarded by President Clinton. Description from PECASE website: The PECASE Award is the highest honor bestowed by the United States government on young professional at the outset of their independent research careers. Eight Federal departments and agencies join together annually to nominate the most meritorious young scientist and engineers who will broadly advance the science and technology that will be of the greatest benefit to fulfilling the agencies' missions.

Friedrichs, C.T., 2001. Class of 1964 Distinguished Professorship. Awarded by the College of William and Mary. From William and Mary memo: Distinguished professorships for associate professors are designed to recognize and reward excellence in research or creative activity and a demonstrated commitment to teaching, and to encourage faculty to remain at the College. Recipients of these professorships will already enjoy a reputation for excellence in scholarship and teaching which suggests that they may be candidates for other distinguished professorships in the future.